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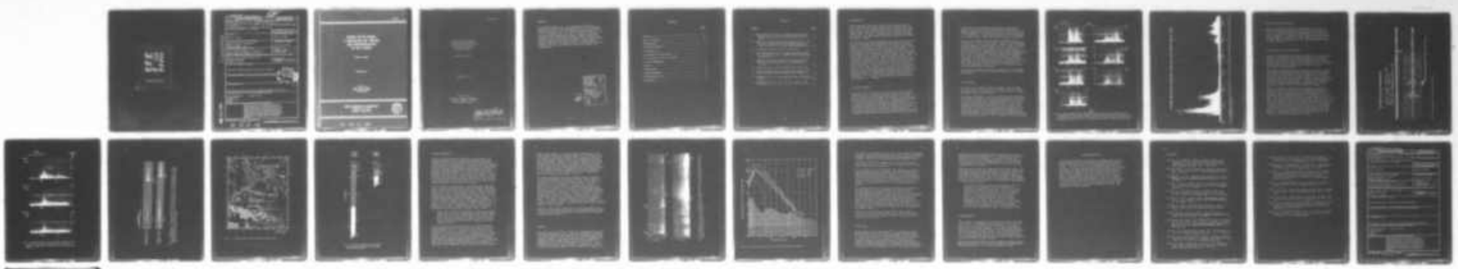

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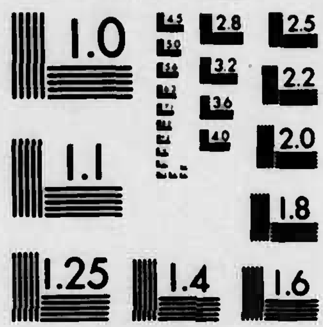

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OCEANIC PN/SN PHASES: A QUALITATIVE EXPLANATION AND REINTERPRETATION OF THE T-PHASE

DANIEL A. WALKER

NOVEMBER 1982

Prepared for
OFFICE OF NAVAL RESEARCH
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HAWAII INSTITUTE OF GEOPHYSICS
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FIGURES

INTRODUCTION

High-frequency Pn/Sn phases were first observed nearly fifty years ago for travel paths in the Atlantic from the West Indies to the northern east coast of the United States (Leet *et al.*, 1951, reported that these observations were made as early as 1935). The history of research on these phases since that time has been given by several authors, with some of the more recent being Molnar and Oliver (1969) and Walker (1977a).

My interest in the phenomenon began in 1963 with the recording of long-range, high-frequency Pn/Sn phases on hydrophones of what was then known as the Pacific Missile Range facility. My efforts at trying to understand these unusual phases (Sn wavetrains greater than Pn wavetrains with frequencies as high as 15 Hz at distances in excess of 3000 km; Walker *et al.*, 1978) has continued since those initial observations. A reasonable, concise summary of my accomplishments prior to this report might be that no answers were found--only more questions. Such methodology can only be rationally tolerated for a length of time much shorter than my tenure on the case. So, for the past few years, it has been hoped that a working hypothesis could be found that would permit many, if not all, of the diverse observational pieces to be fitted together in at least a qualitative sense. Such a hypothesis could then serve as an appropriate starting point for comprehensive and detailed quantitative analyses leading to a generally acceptable model for the generation and propagation of long-range, high-frequency Pn/Sn phases. A working hypothesis has now emerged and is the subject of this report.

SN SIGNAL STRENGTH

One of the most interesting aspects of long-range, high-frequency Pn/Sn propagation in the northwestern Pacific is the strength of the Sn phase (Walker *et al.*, in press). Relative to Pn, Sn often appears stronger at great distances--even at high frequencies (Fig. 1). A possible explanation for these observations begins with considerations of: (1) the efficiencies of Pn/Sn energy transmission across the basement-unconsolidated sediment interface; (2) possible conversions of Pn and Sn at the basement-sediment interface; and, (3) ocean-surface reflections. Observations of conversions upward and across the basement-sediment interface, as well as ocean-surface reflections for short travel paths

off the coast of California are reported in Auld <u>et al</u>. (1969), where data indicate that the percentage of P (perhaps actually Pn) energy converted to S is greater than the percentage of S (perhaps actually Sn) energy converted to P. Examples of ocean-surface reflections are also given in Shimamura <u>et al</u>. (1975) and McCreery <u>et al</u>. (in press).

The very recording of "Pn/Sn" phases on ocean-bottom sediments is evidence that Pn and Sn energy does propagate, by some means, into the sediments. Energy losses above the basement-sediment interface will occur, i.e. not all of the energy passing into the sediments will be returned to the interface by way of reflections from the ocean surface. These losses could be much greater than those produced within that portion of the waveguide below the basement-sediment interface. Furthermore, if the percentage of Sn energy lost after propagation up through the basement-sediment interface, as S or converted P or both, is less than the percentage of Pn energy similarly lost up through this interface, then Sn would retain a greater percentage of its initial energy within that portion of the waveguide below the basement-sediment interface.

Under these assumptions Sn signal strength could increase with distance relative to Pn signal strength--even at high frequencies.

PN WAVETRAINS

In spite of Sn's greater signal strength, its wavetrain is considerably shorter than Pn's (Figs. 1 and 2). This seemingly peculiar observation can be explained by considering other types of conversions.

Any phases, originally Pn or Sn, that pass upward through the basement-sediment interface may eventually be reflected by the ocean surface (or the sediment-water interface) and returned to the basement-sediment interface to continue, somewhat weakened, in the waveguide as Pn or Sn or both. Throughout the travel path to the station, original Pn's returning to the interface and continuing in part as Sn's, as well as original Sn's returning to the interface and continuing in part as Pn's, would arrive between the main Pn and Sn phases. The net effect of such conversions would be Pn wavetrains greater in their duration than Sn wavetrains.

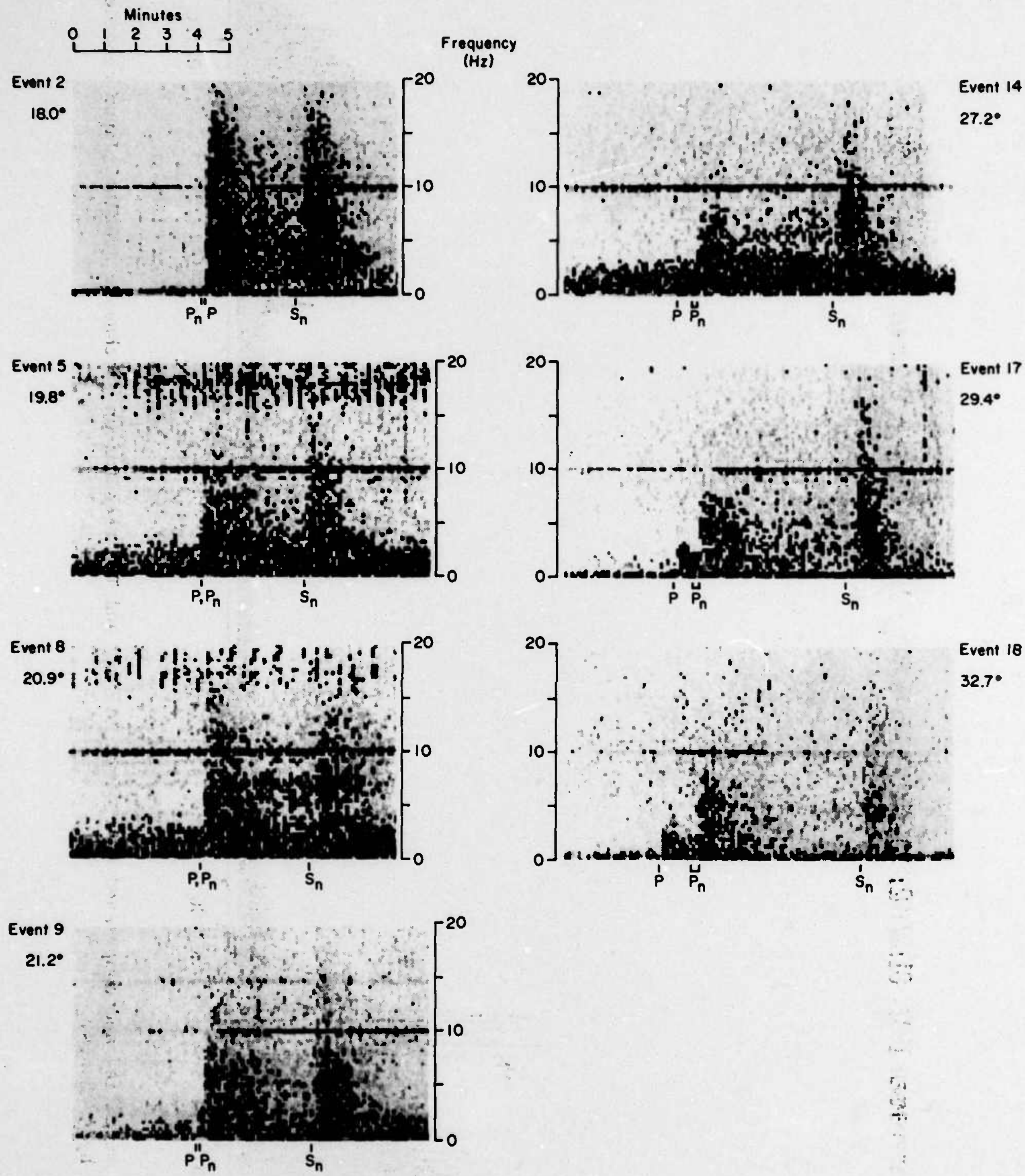

Fig. 1. Spectrograms for some earthquakes having travel paths to Wake under the Northwestern Pacific Basin. Expected times of arrivals are based on either the Jeffreys-Bullen tables (1958) for P or Pn/Sn travel time curves from Walker (1977a). The contour interval is 8 db. The line at 10 Hz is due to time code cross talk.

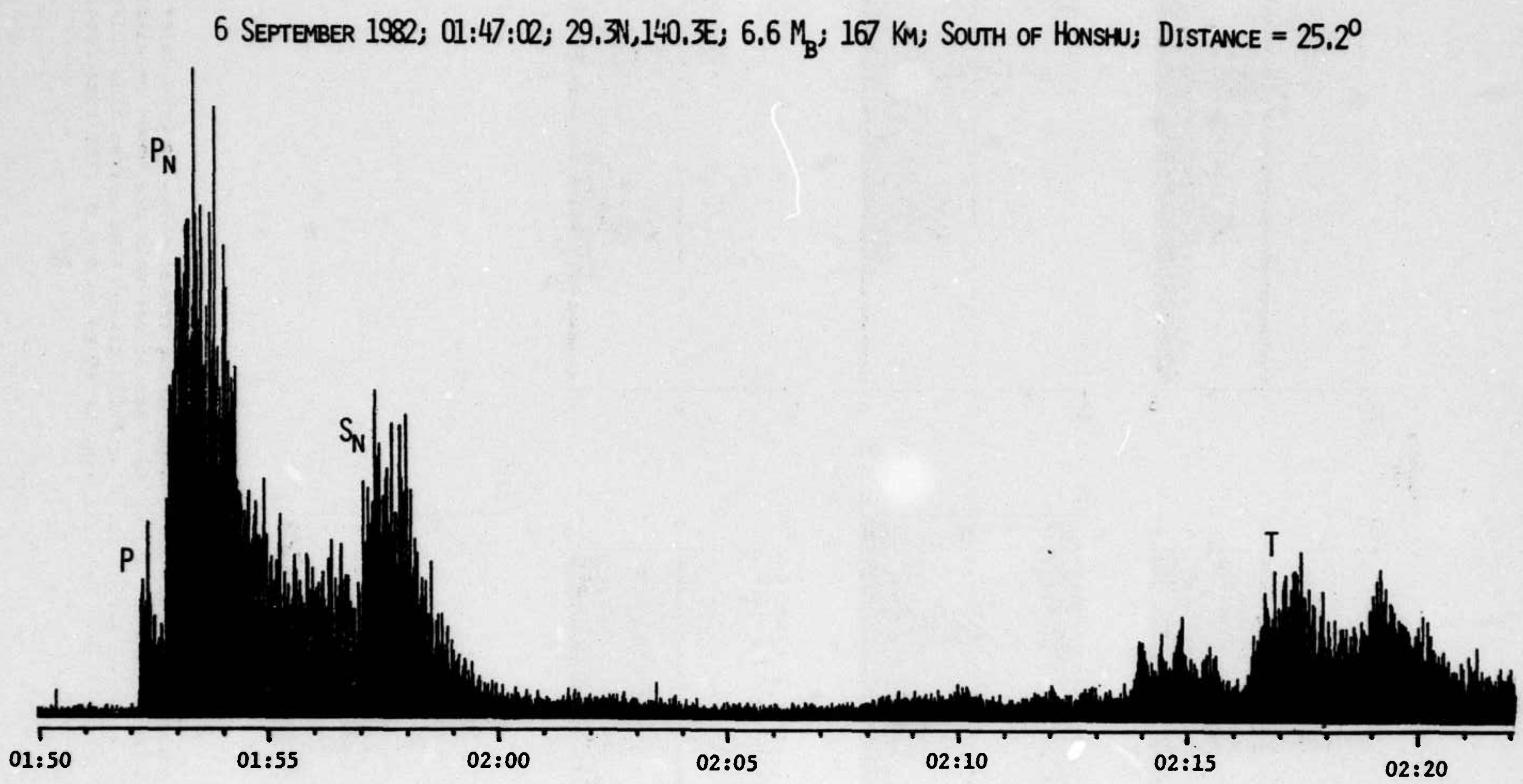

Fig. 2. Digitally rectified and compressed plot of P, Pn, Sn, and T phases for an earthquake south of Japan recorded by the Wake Island hydrophones.

OCEAN-SURFACE REFLECTIONS

Other potentially significant contributors to the Pn, as well as Sn, wavetrains are multiple ocean-surface reflections of all Pn/Sn variations observed on the ocean bottom that are capable of becoming compressional water waves at the sediment-water interface. Such reflections have already been proposed in synthetic Pn model studies (Gettrust and Frazier, 1981). An example of an ocean-surface reflection is shown in Figure 3.

PN/SN PHASES AT GREAT DISTANCES

Another puzzling aspect of Pn/Sn propagation is the frequent absence or weakness of Sn, yet presence of Pn, at great distances (often more than 4000 km) throughout the North Pacific (Walker, 1977a and b) and Central Pacific (Talandier and Bouchon, 1979), in spite of stronger Sn's than Pn's for relatively homogeneous travel paths across the deep Northwestern Pacific Basin.

A possible explanation is that paths other than those across the relatively homogeneous deep Northwestern Pacific Basin are likely to encounter relatively large lateral changes in the crust and upper mantle. These changes would have to be of such a nature so as to reduce Sn signal strength without seriously affecting the Pn phase. Large lateral changes could be produced by plateaus, rises, ridge systems, island and seamount chains, fracture zones, transform faults, fossil arcs and trenches, and rafted continental fragments.

Specific examples of Sn's severely attenuated by large lateral variations are found in recordings of earthquakes from the Solomon Islands area on the Wake hydrophones. Although these events are at distances comparable to events from Japan and the Kurils which have strong Pn/Sn phases (Fig. 1), only their Pn's are well recorded (Fig. 4). Furthermore, this effect cannot be attributed to differences in source mechanisms because Sn's from the area are well recorded at Ponape (examples of such recordings are shown in Fig. 5; refer to Fig. 6 for the location of Ponape). A reasonable explanation would appear to be the large structural changes associated with the transition from the shallow Ontong Java Plateau to the deeper Northwestern Pacific Basin (Figs. 6 and 7). An additional factor may be the extension of the Caroline Archipelago through this region.

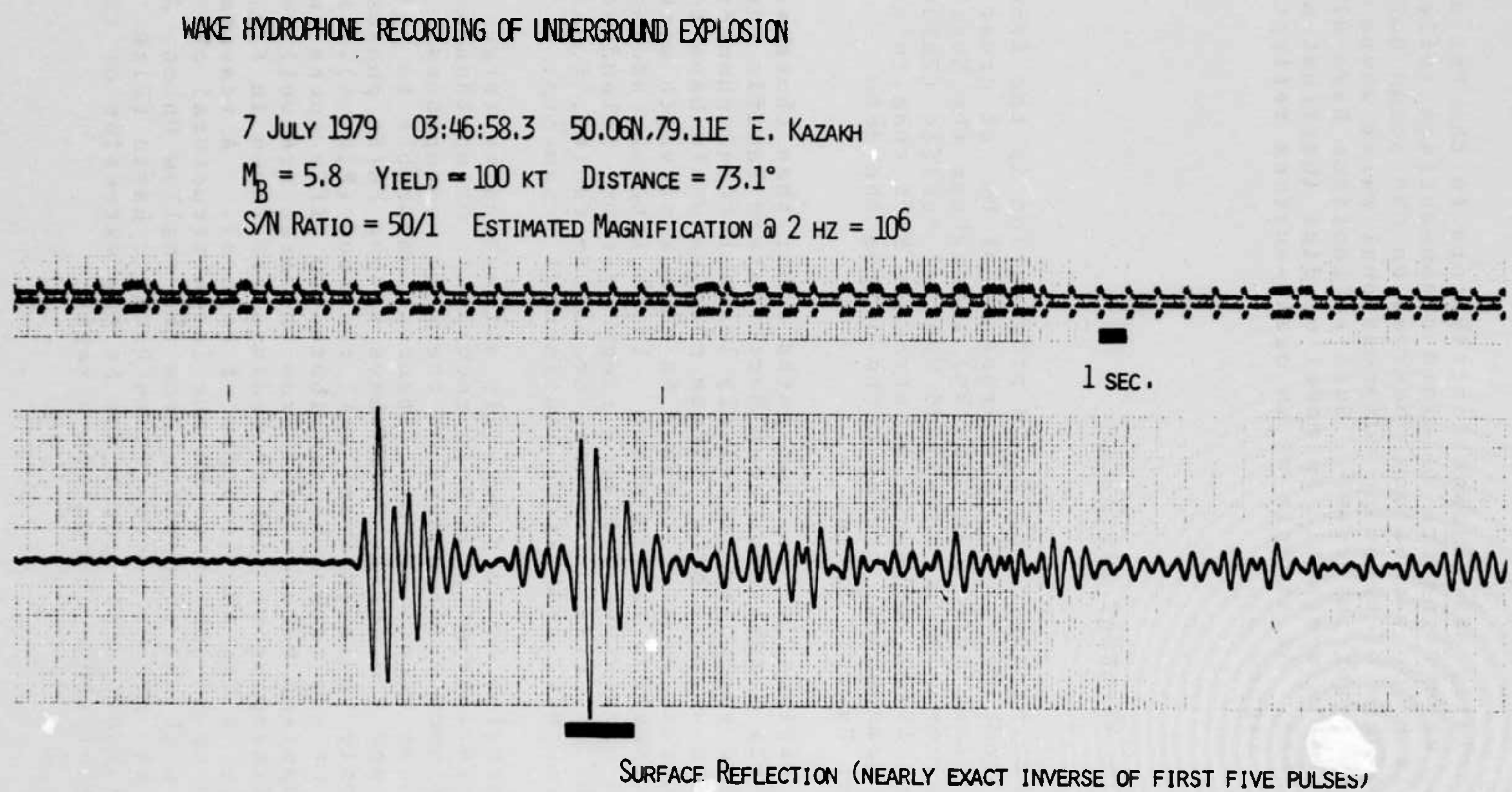

Fig. 3. An example of ocean-surface relfections.

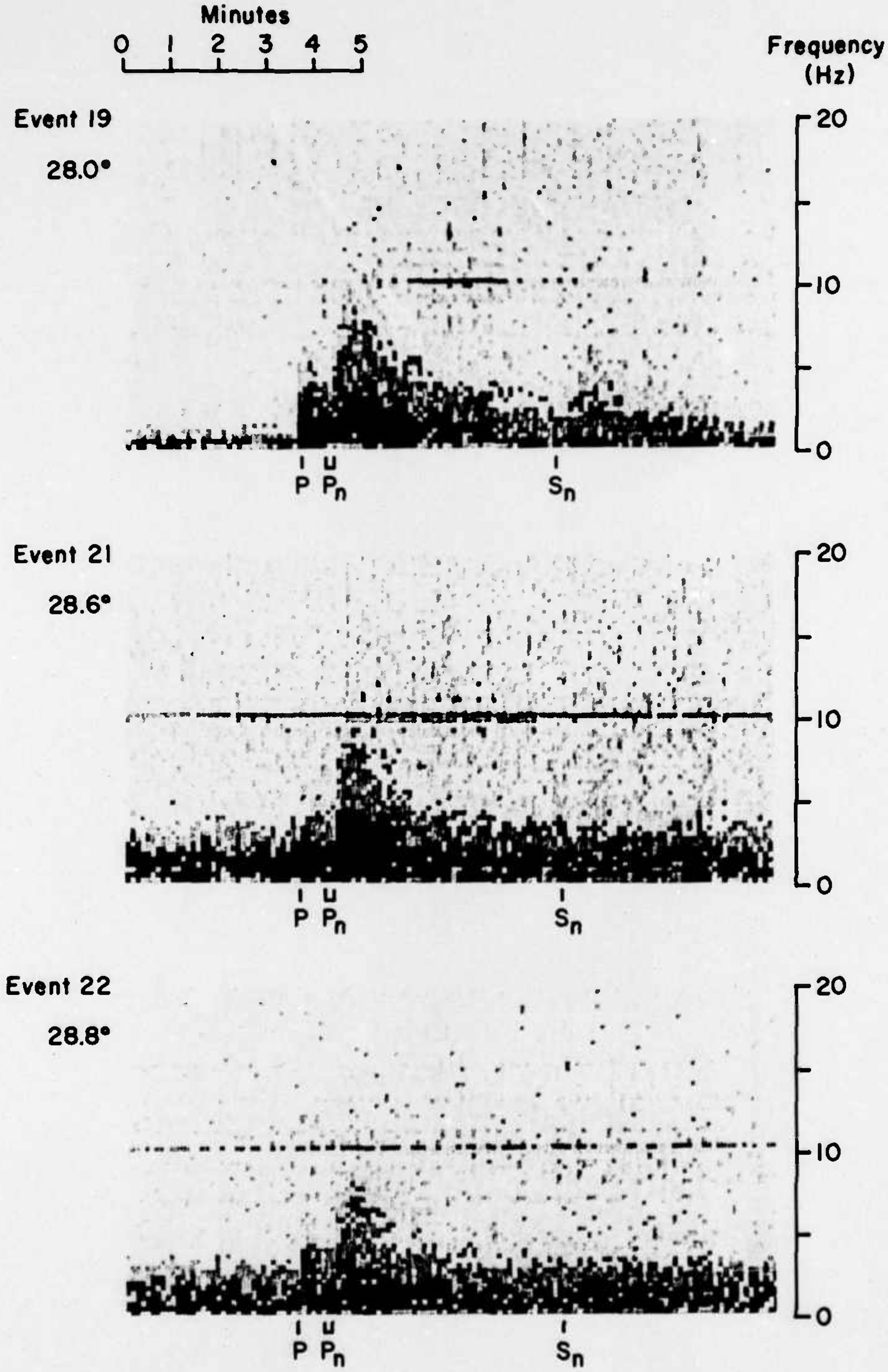

Fig. 4. Some spectrograms for earthquakes having portions of their travel paths to Wake under the Ontong-Java Plateau. Computational procedures are the same as used in Fig. 1.

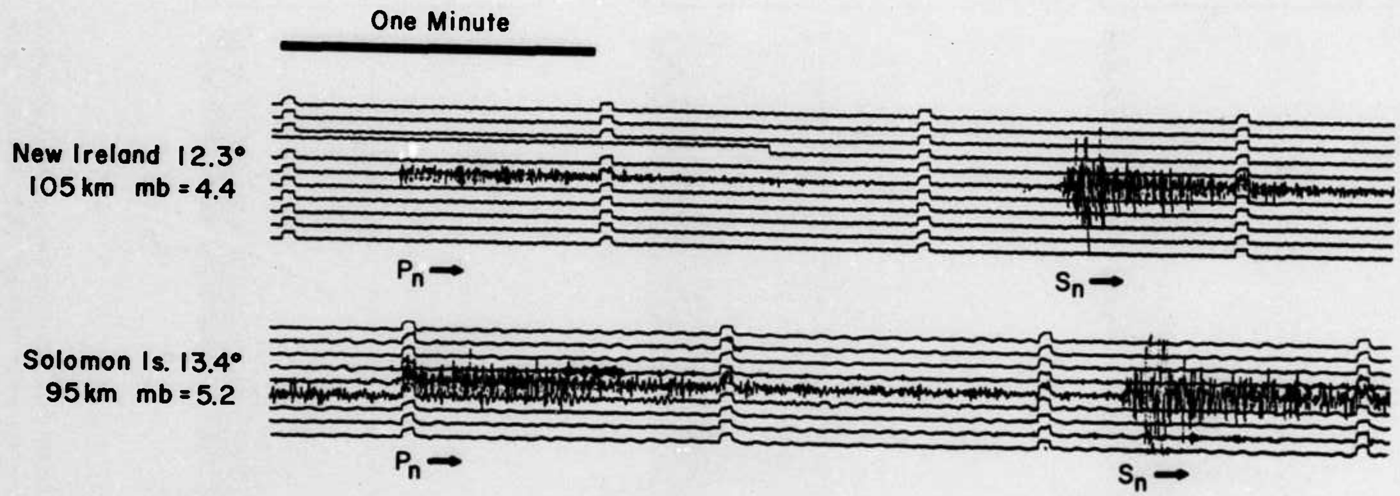

Fig. 5. Examples of Pn and Sn phases recorded at Ponape on the northern margin of the Ontong-Java Plateau. Of more than forty events from the New Ireland-Solomon Islands area, amplitudes of Sn phases are at least comparable to, and frequently larger than, those of their respective Pn phases.

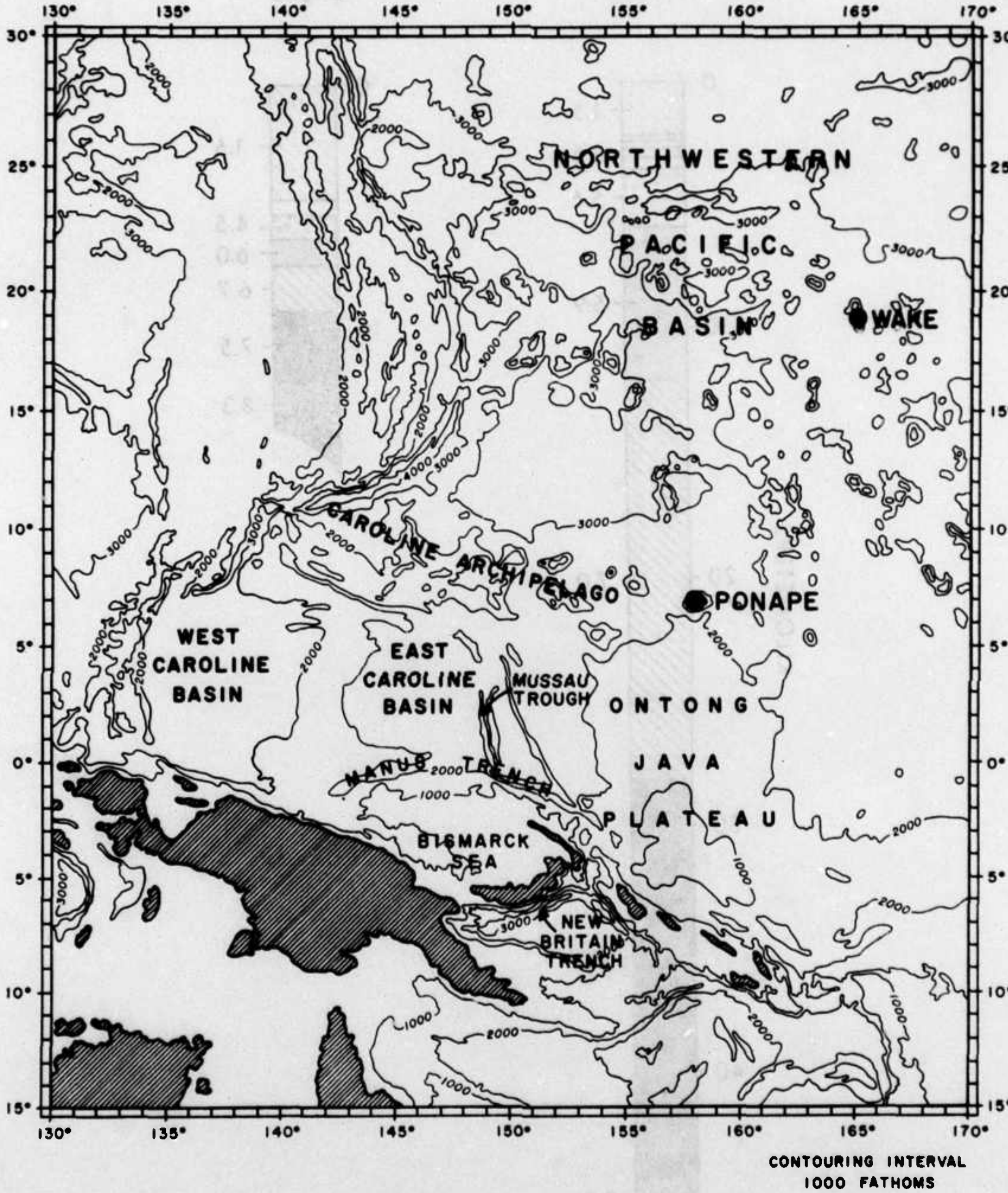

Fig. 6. Bathymetry map of the Northwestern Pacific area.

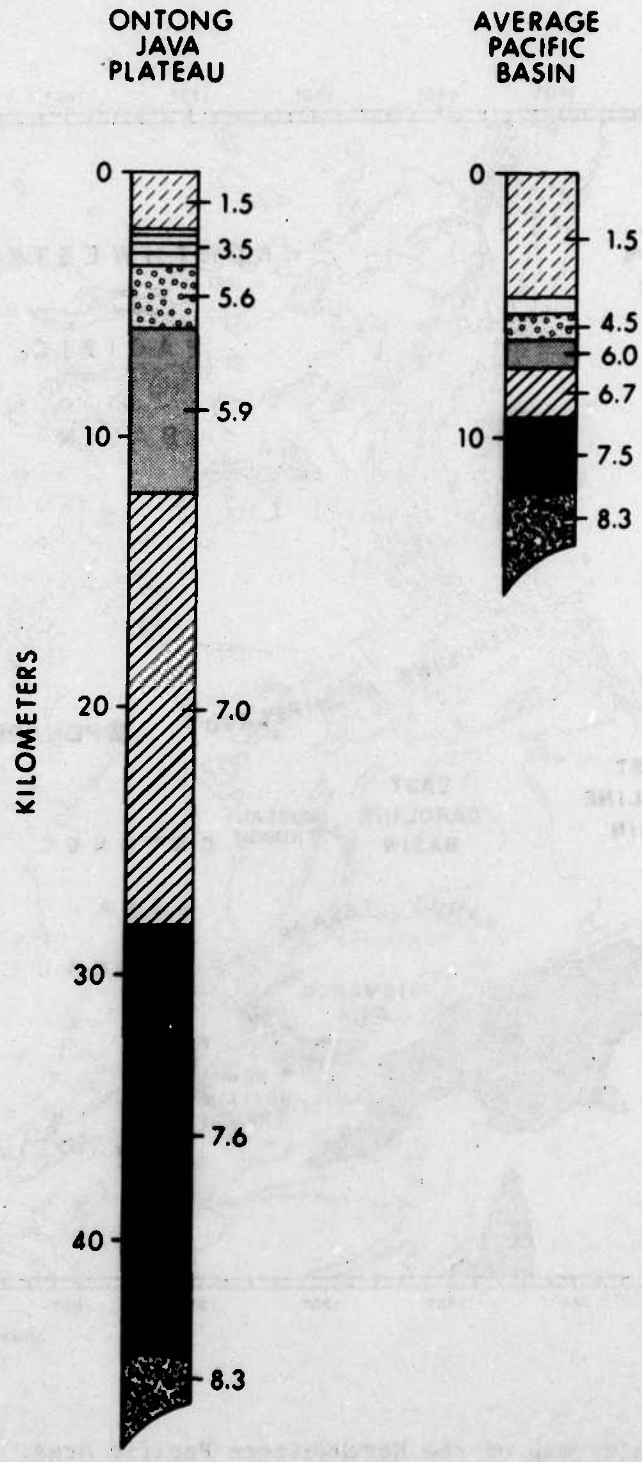

Fig. 7. Section profiles for the Ontong-Java Plateau and Pacific Basin (from Hussong et al. 1979).

T-PHASE MECHANISMS

Tolstoy and Ewing (1950) recognized the importance of a sloping bottom in the production of T-phases, and Milne (1959) provided a specific mechanism involving multiple reflections between the surface of the ocean and its downward sloping bottom. Although such a mechanism could be significant for T-phases originating in areas with the appropriate downward sloping bottom, many strong T-phases have been observed from regions where the ocean floor is level or at a greater depth than adjacent areas in the direction of the receiver (Johnson et al., 1968; Duennebier, 1968). Included among these regions are the deep ocean floor off the coast of California and Oregon, the deep ocean floor south of the subducting margins of the Northern Pacific and east of the Western Pacific, and the East Pacific Rise.

Because of these observations, a mechanism other than downslope propagation is required. Some suggestions included ocean surface scattering (Johnson et al., 1968), scattering from the sea floor by fault scarps near the source (Johnson and Norris, 1970), and coupling of Stoneley waves into the SOFAR channel (Biot, 1952; Duennebier, 1968). All of these proposed mechanisms, including downslope propagation, presume that the energy of the T-phase comes ultimately from P and, perhaps, S phases travelling upwards through the crust to the ocean bottom near the T-phase source location; however, with such a presumption, none of the proposed mechanisms is capable of explaining T-phase forerunners. In describing these forerunners, Johnson (1963) stated:

> "The time of earliest perceptible arrival is probably primarily a function of magnitude as the signal emerges slowly from the ocean background noise...Early, low-level arrivals, undetected in most T-phase recordings, must be normal-mode ground waves or, at least, must have followed a ground path for a significant portion of their travel."

He also states that in one instance (a 7.0-Ms earthquake from the Kurils) the forerunners were so early that "the transformation from P or S waves to sound channel waves would have to occur at a distance of about 17 to 21° from the source toward the receiver." In describing a P, S, and T phase (Fig. 8; actually the P and S phases are Pn and Sn phases) from a large (6.2 mb) earthquake in the Marianas recorded on hydrophones near Enewetok Atoll at a distance of about 18°, Duennebier (1968) notes that "the T phase does not have a definite onset and that energy was continuously received at the hydrophone after the arrival of the P wave."

Both authors suggest that the apparent coupling into the SOFAR channel was due to normal, mantle P or S waves or both refracted by the Emperor Seamount Chain (Johnson, 1963) and by several groups of seamounts in the Northwestern Pacific Basin (Duennebier, 1968). In terms of frequency content and strength of signal, however, the energy from the long-range, high-frequency, guided Pn and Sn phases seems more likely to be coupled into the SOFAR channel than the mantle-refracted P and S phases which are extremely weak at high frequencies. At teleseismic distances frequencies of P and S generally do not exceed 3 or 4 Hz, while Pn, Sn, and T frequencies may be as high as 20 Hz (Figs. 8 and 9).

For large earthquakes sufficient energy could be contained in the Pn/Sn phases for coupling into the SOFAR channel throughout the travel path to the receiver. This coupling could occur by any of the mechanisms proposed for the generation of the T-phase (i.e., scattering or Stoneley waves or both), with seamount enhancement remaining as an important consideration. In effect the Pn/Sn phases would serve as potential sources of energy at the sediment-basement (or water-sediment) interface. As Pn/Sn energy declines with increasing distance, the amount of energy coupled into the SOFAR channel would also decline, thus producing a T-phase signal which would slowly emerge from the ocean background noise. A recently recorded example of such an emergent T-phase is shown in Figure 2. Energy arriving at 02:08 corresponds to a Pn path of 9.6° at 8.0 km/sec and a T-phase path of only 15.6° at 1.5 km/sec.

Finally, an additional explanation for Sn appearing to have relatively more energy than Pn with increasing distance could be that Pn energy is coupled more efficiently into the SOFAR channel than Sn energy is.

SUMMARY

Vast regions of the world's oceans are characterized by thinly layered, homogeneous crustal and uppermost mantle structure. This report suggests that comprehensive observations of high-frequency phases, often referred to as Pn/Sn, throughout the Western, Northern, and Central Pacific may be explained by a waveguide which extends upward from the uppermost mantle through the crust and, to some extent, into the sedimentary layers and the entire water column. Pn energy is more efficiently propagated upward into the sedimentary column than

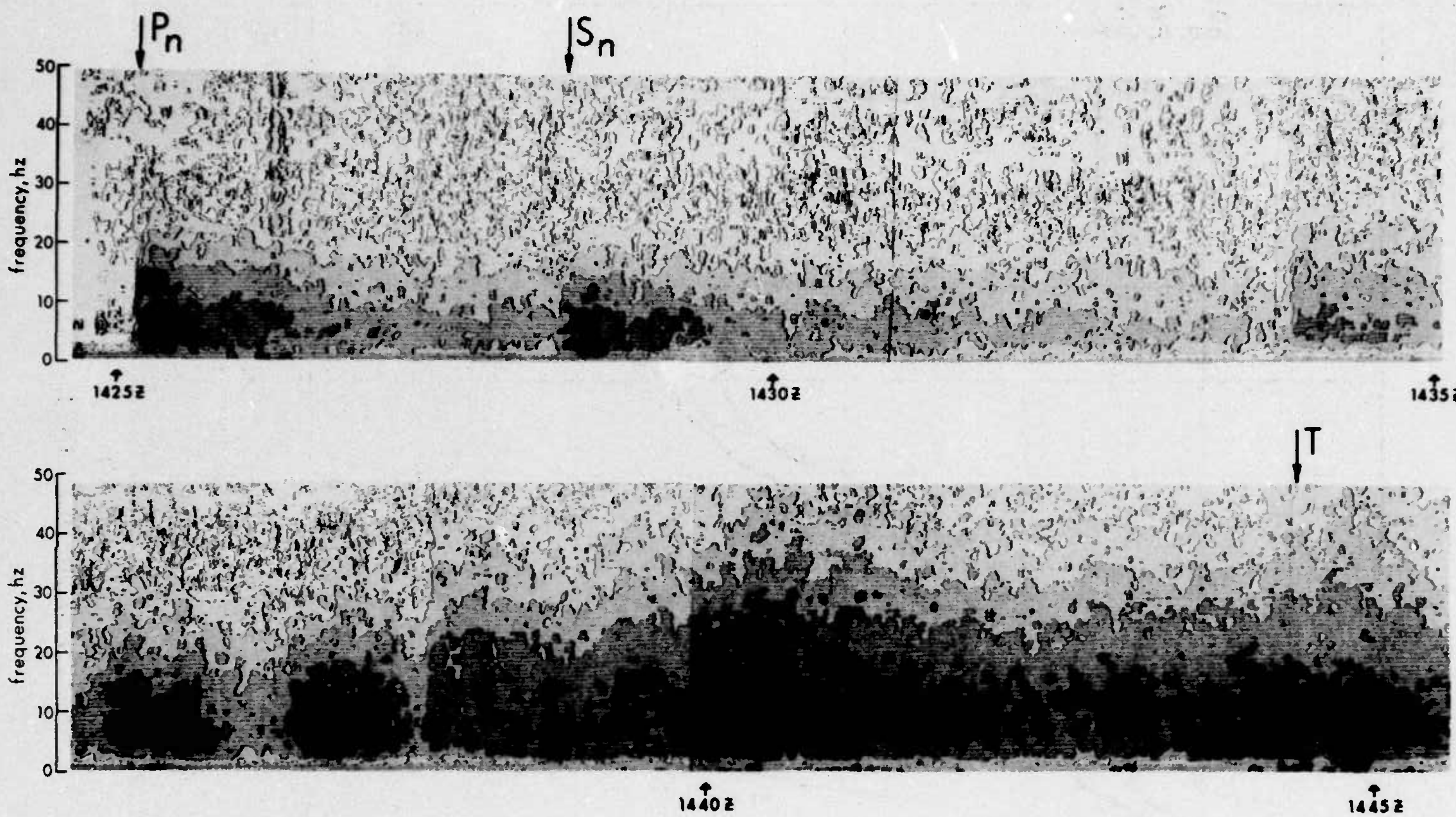

Fig. 8. Sonogram of Pn, Sn, and T phases (after Duennebier 1968). Note that the T-phase does not have a definite onset. Instead, energy appears to be continuously received at the hydrophone after the arrival of the P wave.

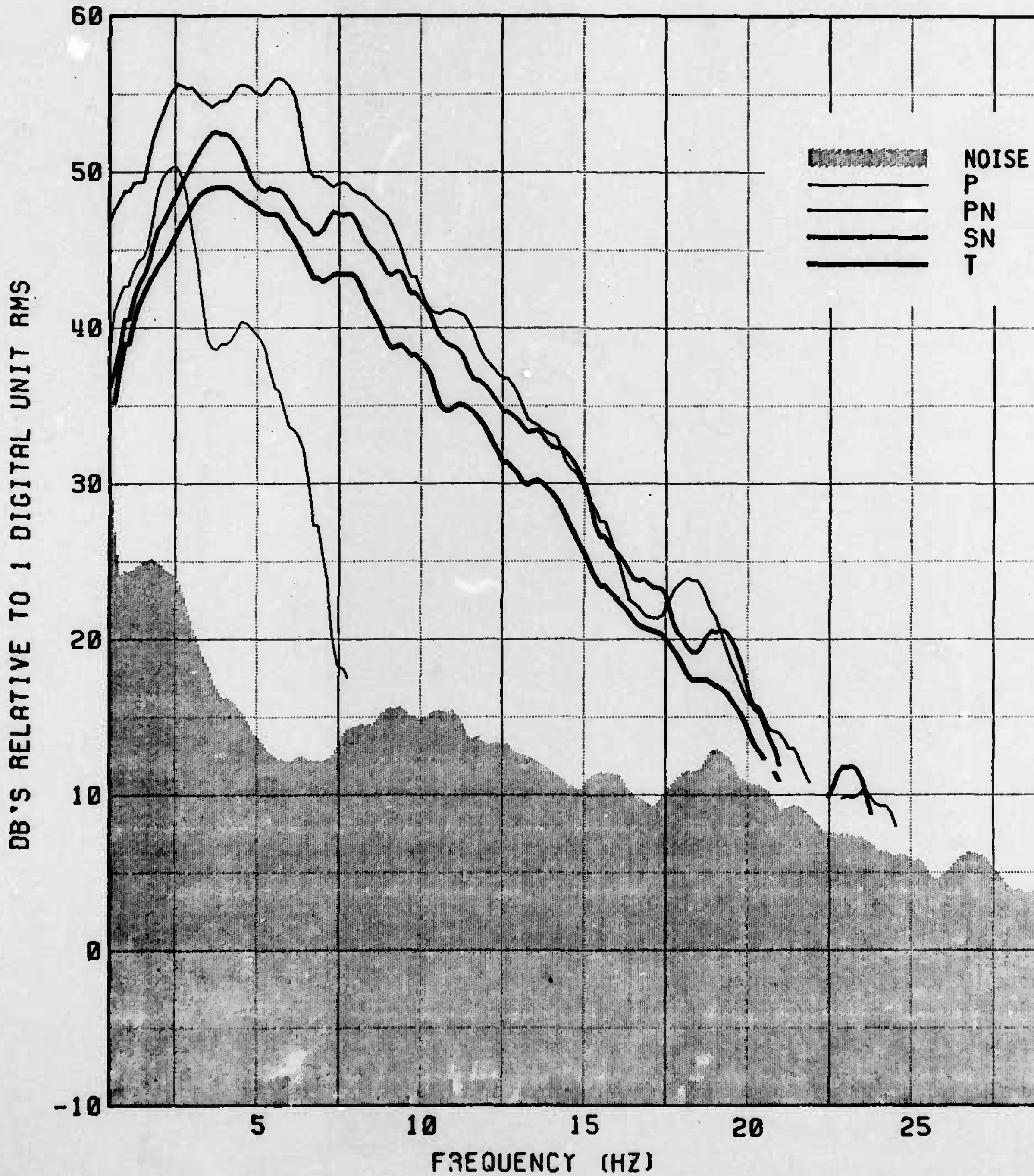

Fig. 9. Spectrums for the P, Pn, Sn, and T phases shown in Figure 2.

Sn energy, and, because of this, Pn is more rapidly attenuated than Sn. As distance increases, Pn's losses above the basement-sediment interface produce a relative strengthening of the Sn phase, such that Sn eventually has more energy than Pn.

The observed data also suggests that the long Pn/Sn wave-trains may, in part, be the result of multiple ocean-surface reflections near the receiver.

Pn to Sn and Sn to Pn conversions are suggested to explain Pn wavetrains consistently longer than the wavetrains of Sn. These conversions could occur when Pn or Sn energy passes through the basement-sediment interface and is returned to that interface by way of reflections from the ocean surface to continue in the waveguide, at least in part, as Sn or Pn phases. Such conversions might be produced at any of the interfaces encountered by Pn or Sn, or their converted phases.

In conjunction with the scattering mechanisms and Stoneley wave propagation already proposed to explain T-phase observations, Pn/Sn phases as sources of energy at the sediment-basement interface could explain: (1) the generation of T-phases in regions not having the downward sloping ocean bottom required by the classical downslope mechanism of Milne (1959) and (2) T-phase forerunners extending well ahead of the peak arrivals--occasionally beginning perhaps as early as the Pn and/or Sn phases. Also, another explanation for Sn having more energy than Pn is provided if Pn energy is more efficiently transmitted than Sn energy into the SOFAR channel.

Finally, the observed data suggest that large lateral variations in the crust and upper mantle may produce significant reductions in Sn signal strength without seriously affecting the Pn phase.

CONCLUSIONS

Although many puzzling observations of long-range oceanic Pn/Sn phases may be resolved by the suggestions presented in this report, many of these suggestions can, and should, be tested quantitatively. These analyses could include the re-examination of existing data, new experiments, and theoretical modeling efforts leading to the generation of complete synthetic seismograms. Furthermore, one should not forget that the mechanisms for the generation and propagation of the main Pn and Sn phases are still not generally agreed

upon, nor have proposed models been matched in a comprehensive manner with observations. Such tasks are of utmost importance if the phenomenon is to finally achieve the status it deserves as a major geophysical feature and tool for mapping the crust and uppermost mantle of the world's oceans--this after nearly fifty years of being little more than an obscure curiosity.

Regarding the T-phase, it seems appropriate that the earth's most efficient acoustical waveguides, the SOFAR channel and the Pn/Sn waveguide, finally should be related; and in the hypothesis formulated in this report, the SOFAR channel is energized by leakage from the Pn/Sn waveguide. The recognition of this relationship could be an important, and perhaps critical, factor in arriving at a comprehensive understanding of these oceanic phases.

> "In the bulletin of the Harvard Seismograph Station, under date of September 15, 1935 attention was directed to the unusual character of certain records from the vicinity of 17°N, 62°W. One of the novel features was a short-period phase about 23 minutes after P. It has become known as T, for third, with P and S constituting the first and second groups of short-period waves of similar general appearance...Actually, many features of P and S are abnormal on this and later records from certain areas at this distance range, and work on that part of the problem is in progress, but the investigation of T has been undertaken first." (Leet et al., 1951)

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Special appreciation goes to Charles McCreery, George Sutton, and Loren Kroenke for constructive comments and discussions. Editorial assistance was provided by Barbara Jones.

SUPPLEMENTARY NOTE

It may be appropriate at this time to suggest that a new name be given to the high-frequency compressional and shear phases often observed at great distances in the world's oceans. The difficulty with the nomenclature used to date is that: (1) an, as yet, unsubstantiated relationship to the well known and much studied longer-period Pn/Sn phases of continents is inferred; and (2) the environmental feature most strongly linked to the observations is not cited. Thus, a more logical term would be "Ocean P" or "Ocean S" with the abbreviations being "Po/So." With this change, those unfamiliar with the phenomenon would not be as likely to make the false assumption that the phases are similar to continental Pn and Sn. Such assumptions in the past have been a major stumbling block in stimulating interest and support for "Po/So" research.

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